2002

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DEVELOPMENT OF HIGH EFFICIENCY BRUSHLESS DC MOTOR WITH NEW MANUFACTURING METHOD OF STATOR FOR COMPRESSORS

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ABSTRACT

To promote energy saving, we developed a high efficiency brushless DC motor with a new manufacturing method of a stator for compressors. This motor consists of a concentrated winding stator and an interior permanent magnet rotor. The stator has the core structure that we call “a joint-lapped core”. The joint-lapped core is able to open and bend in reverse. While winding the coil, the joint-lapped core is bent in reverse on the connecting joint axis. The coils are wound around the teeth in aligned position. After that, it is bent to form cylindrical core shape. This manufacturing method reduced copper loss. Furthermore, we adopted a 6-pole motor in place of a conventional 4-pole. As a result, iron loss was also reduced, and the high efficiency brushless DC motor was achieved. The noise was also been reduced because of the 6-pole motor.

INTRODUCTION

High efficiency brushless DC motors (permanent magnet motors) for compressor are adopted from the standpoint of energy saving in recent years. However, high efficiency motors have problems of high noise. We are required to achieve high efficiency and low noise. We developed a new motor, and we were able to satisfy this requirement. In this paper, we describe about the new structure and the new manufacturing method of the motor.

STRUCTURE OF THE COMPRESSOR

Fig. 1 shows a cross section of the newly developed compressor, Fig. 2 and Fig. 3 shows cross sections and side views of the new motor and the conventional motor for compressors. The conventional motor, which is used for the power source of compressors made by our company, consists of a distributed winding stator of 3-phase, 4-pole, 24-slot and an IPM (Interior Permanent Magnet) rotor. On the other hand, the newly

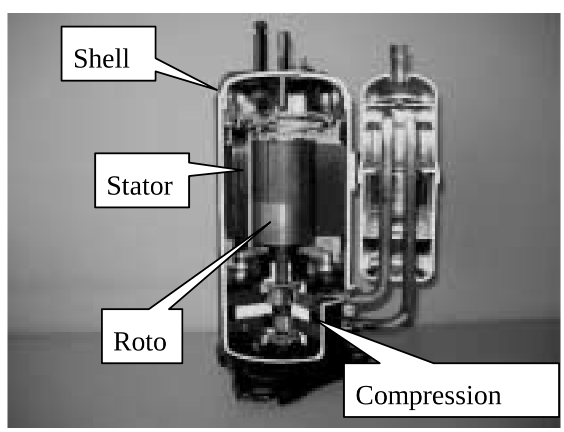
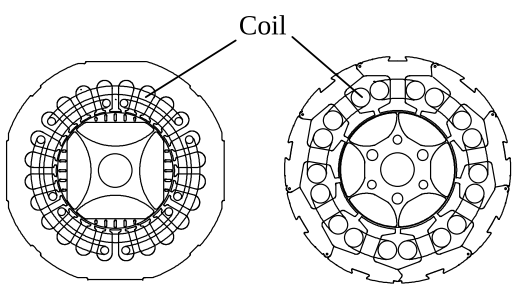


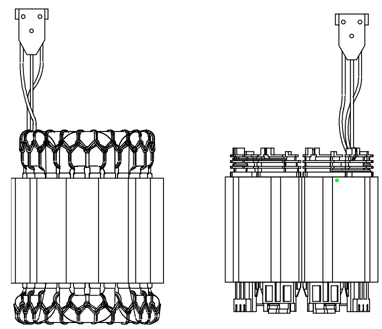
Fig. 1 Cross section of new compressor

developed motor consists of a concentrated winding stator of 3-phase, 6-pole, 9-slot and an IPM rotor. This stator has the new core structure that we call “a joint-lapped core”. This rotor has six pieces of convex lens shaped magnets (convex to both inner diameter side and outer diameter side in the cross section) embedded into the rotor core.



(a) Conventional motor (b) New motor

Fig. 2 Cross section of motor



(a) Conventional motor (b) New

Fig. 3 Side view of motor

STUDY OF HIGH EFFICIENCY MOTOR

Losses that occur in a motor are divided roughly into copper loss and iron loss (hysteresis loss, eddy current loss). Since the copper loss is given by I^2R (I: coil current, R: coil resistance), we can reduce the copper loss by decreasing the coil current or the winding resistance. To reduce the winding resistance, we reduced the coil length and we improved the coil space factor. We developed a concentrated motor with this new manufacturing method, and achieved high efficiency. The following paragraphs describe how the motor losses were reduced and about the new manufacturing method.

STRUCTURE OF THE MOTOR AND MANUFACTURING METHOD

<u>Reduction of coil length</u>

Fig. 2 shows the structures of our conventional motor and our new motor. The conventional motor is called a distributed winding motor, in which the coils wound in advance are inserted inside the stator slots. Since its coils are arranged across the core end faces, it has a problem with the coil length becoming too long.

On the other hand, we adopted the concentrated winding method in the new motor. Since the coils of the concentrated winding stators are directly wound onto insulators covering the stator tooth, they would be shortened in comparison with the coils of the distributed winding stators.

Improvement of coil space factor

Although the best method to improve the coil space factor (=D^2N/S, where D: diameter of coil, N: number of turns, S: area of slot) is to wind the coils in alignment perfectly, there is a limit to what the distributed winding stators can do, because their coils are wound onto the jig in advance and after that they are inserted inside the stator slots.

On the other hand, the coil space factor of the concentrated winding stator makes a great difference to the structure and the method of manufacturing. They can be classified as follows. They are the cylindrical core as shown in Fig. 4.1, the separate core in Fig. 4.2, the thin bridge core in Fig 4.3 and the newly developed core (joint-lapped core) in Fig. 2 (b), Fig. 3 (b).

The cylindrical core, which is started to use for compressors, is not separated. Since the stator employing this core is manufactured by inserting the winding nozzle that is wound around the teeth into the slots of the core, it is difficult to wind in alignment. In addition, the coils cannot be wound on a turning orbit of the nozzle, therefore extra dead space occurs and high space factor (coil density) cannot be achieved.

The separate core is separated into each tooth unit. After this each tooth unit is laminated by using a press machine, the coils are wound onto the teeth in alignment at the outside place. Thereafter, the teeth are combined so as to form a cylindrical form integrally by welding. Although it can achieve a high space factor, it has disadvantages of

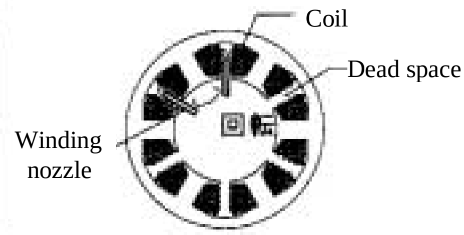


Fig. 4.1 Cylindrical core

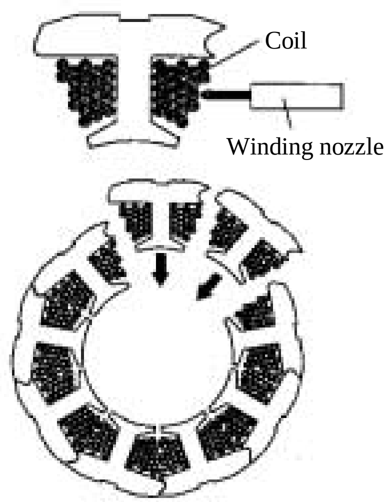


Fig. 4.2 Separate core

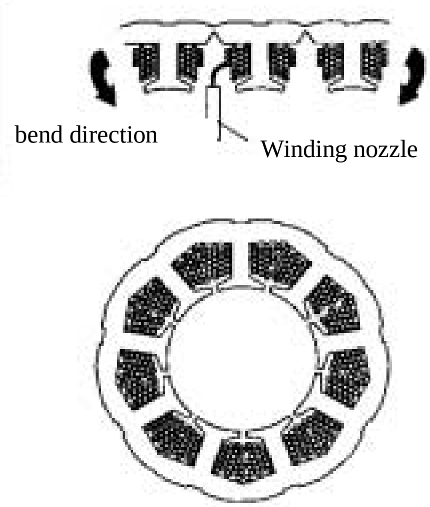


Fig. 4.3 Thin bridge core

high noise and high vibration because a circularity of the core inside diameter is not accurate for a wide tolerance of the teeth configuration and assembly. Besides, it has the disadvantage of increasing components of this stator.

The thin bridge core is a separate core connected by thin bridges. It is pressed in linear shape, then the coils is wound around the teeth of the thin bridge core in linear state, after that it is bent to form a cylindrical core shape, finally it is made integral by welding. Since this can reduce a number of components, this can improve productivity. Furthermore, its space factor can be improved in comparison with a cylindrical core since it has enough space for a turning orbit. However, if the length of core stack is long range or the coil is thin range, it would make a low space factor in comparison with the separate core that does not depend on neighboring teeth when winding coil.

The joint-lapped core that we developed is able to open and bend in reverse. The coils are wound around the teeth in an aligned position like the separate core. The joint-lapped core doesn't have the disadvantages of the aforementioned cores. By using this core, we can get good productivity like a thin bridge core and good core accuracy like a cylindrical core. The following paragraph describes the structure of this core.

Joint-lapped core

The Structures of the thin bridge core and the joint-lapped core are compared in Fig. 5. The thin bridge core is bent at the thin bridge portions, and then every neighboring tooth unit is brought together simply.

On the other hand, the joint-lapped core is overlapped at each side of each tooth unit. Also,

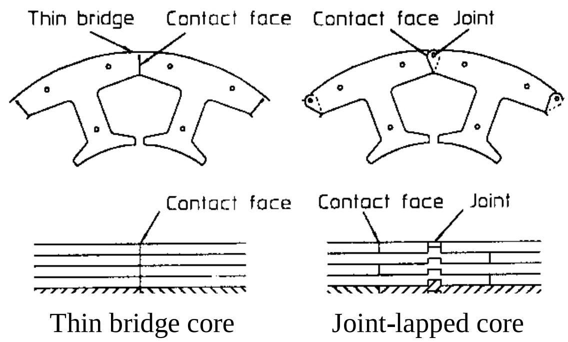


Fig. 5 Comparison of connected portion

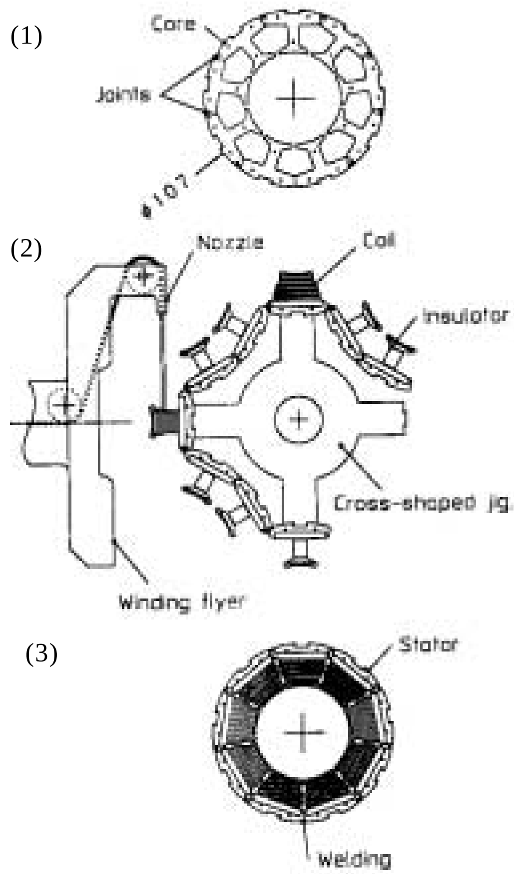


Fig. 6 Winding method of the joint-lapped core

the joint-lapped core has concave and convex joints around the center of its overlapped area. Every tooth unit is connected by these joints. Since the joints are cylindrical shapes with small clearance, the joint-lapped core can be bent backward and forward on the joint axis many times without any damage. This structure made it possible for the coils to be wound around the tooth units without contacting the winding nozzle and neighboring tooth since it can be bent in reverse. (See Fig. 6) Perfect alignment was achieved using this structure and this manufacturing method. In addition, dead space that was produced by insertion of a nozzle into slots was decreased. As a result, we were able to reduce coil resistance by using thicker coils, because effective slot cross area was increased. In addition, since tooth units of the joint-lapped core are connected by the concave and convex joints, handling of the assembly was made easier.

Fig. 7 shows a photograph of a cross section of a joint-lapped core motor. It shows that perfectly

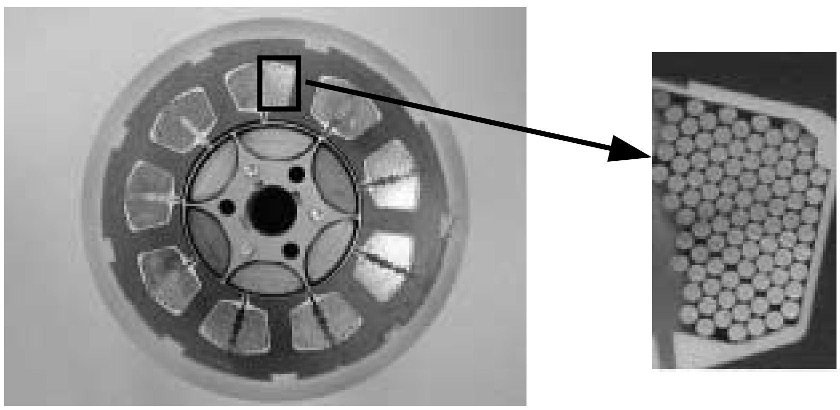


Fig. 7 Cross section of joint-lapped core motor

aligned coil and a high space factor were achieved. Compared with a conventional cylindrical core motor with a space factor of 75%, the joint-lapped core motor was achieved a space factor of 95%. Thus, the concentrated winding motor using the joint-lapped core was able to decrease coil resistance by approximately 50% by means of a high space factor and reduction of coil length.

INCREASE OF POLE NUMBER

A concentrated winding motor contains harmonic components of the magnetic field, since the magnetic field of the motor is distributed asymmetrically in comparison with a sinusoidal magnetic field of a distributed winding motor. Because of the harmonic components, magnetic flux

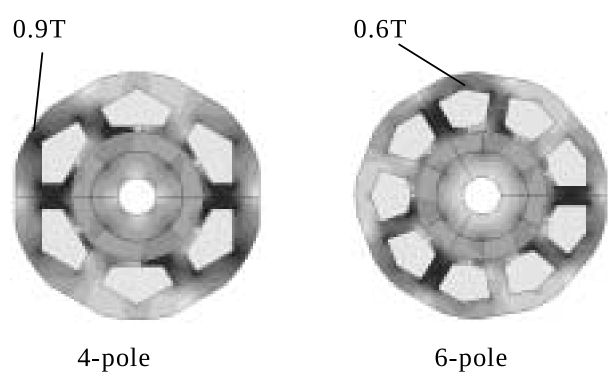


Fig. 8 Flux distribution

density of the motor is increased in parts, and iron loss is increased in comparison to distributed winding motor. The motor was not able to vastly improve efficiency, because copper loss decreased while iron loss increased. We examined decreasing magnetic flux density on the stator core to improve the above problem.

Magnetic flux density (analyzed by the FEM) of a 4-pole concentrated winding motor and a 6-pole concentrated winding motor are compared in Fig. 8. (4-pole is adopted generally in a brushless DC motor for compressors)　As can be seen from this analysis, magnetic flux density of the core back is decreased from 0.9tesla to 0.6tesla, because the magnetic flux is dispersed by changing from 4-pole to 6-pole. In order to examine the effect of decreasing magnetic flux density and an increase in the frequency of the rotating magnetic field (1.5 times = 6/4), we tested these two motors. The result of this test is shown in Fig. 9. This shows the components of motor loss at rated load (3180r/min, 1.63Nm). It can be seen that the effect of decreasing magnetic flux density is larger than the effect of increasing the frequency of the rotating magnetic field.

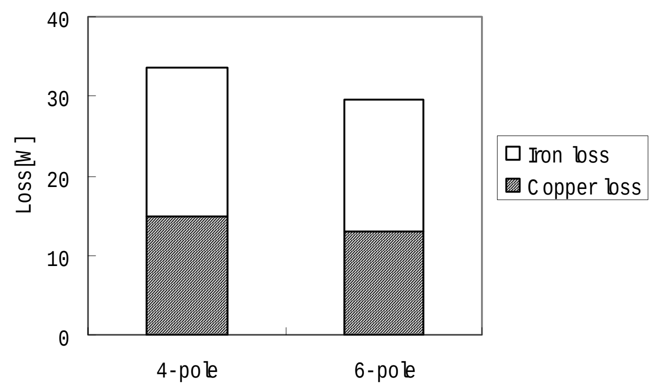


Fig. 9　Motor loss (3180r/m, 1.63Nm)

In addition, in the case of a concentrated winding motor with a cylindrical core, if the pole number is increased (ex. from 4-pole, 6-slot to 6-pole, 9-slot), dead space of the nozzle is increased and copper loss is increased because of a decreased space factor. However, copper loss is not increased since dead space does not occur in the joint-lapped core motor. Also, the coil length can be decreased by 13% since the coil turn number per tooth can be decreased by a change to 6-pole.

PERFORMANCE OF THE MOTOR (TEST RESULT)

Efficiency

Fig. 10 shows the motor efficiency at various levels of output using on air-conditioners at 200W to 1.2kW for the 6-pole concentrated winding motor with the joint-lapped core, the 4-pole concentrated winding

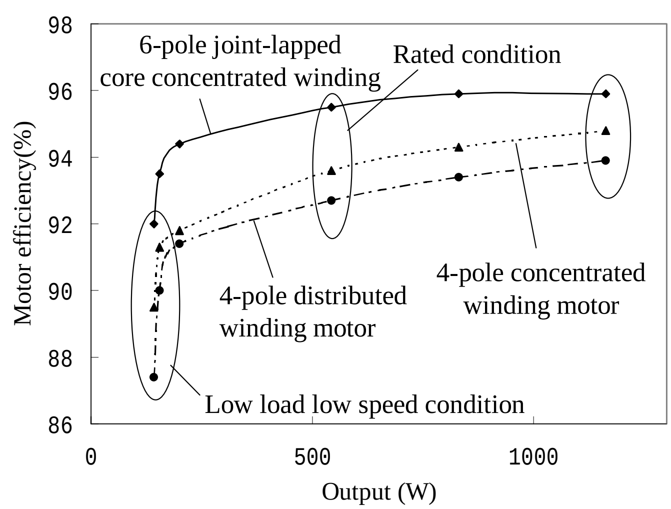


Fig.10　Comparison of motor efficiency

motor with the cylindrical core and the 4-pole distributed winding motor. This shows that the efficiency of the joint-lapped core motor was improved in the entire range, especially in low output range. It is improved by 5% under the condition of low load low speed, by 3% under the condition of rated load rated speed in comparison with the conventional 4-pole distributed winding motor.

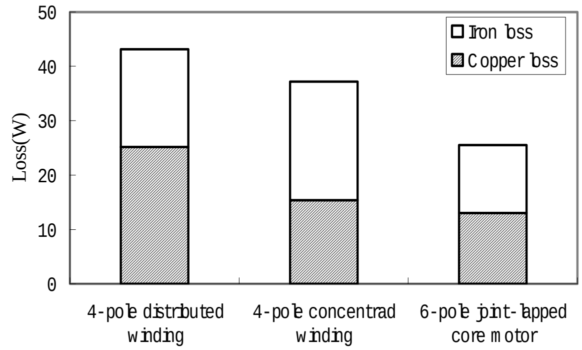


Fig. 11 Comparison of motor loss

The components of loss for each motor at the condition of rated torque rated speed are shown in Fig. 11. Compared to the 4-pole distributed winding motor, copper loss is decreased by 40%, but iron loss is increased by 20%. Therefore, motor efficiency is improved by only 1%.

On the other hand, the 6-pole concentrated winding motor with the joint-lapped core was able to decrease both copper loss and iron loss (increase in copper loss is 50%, increase in iron loss is 20%), motor efficiency was improved by 3%.

<u>Noise</u>

The noise and vibration of a concentrated winding motor is higher than a distributed winding motor's, since a concentrated winding motor produces harmonics of the magnetic field at its air gap. In order to solve the above problem, we changed the pole number from 4-pole to 6-pole and designed a convex lens shaped magnets rotor, which was embedded six pieces of convex lens shaped magnets close to the rotor core surface. Therefore, mode of magnetic exciting force was shifted from mode 2 to mode 3, and the dynamic-rigidity was increased. As a result, we were able to reduce the noise level and the vibration level. The noise level of compressors with joint-lapped core motors at various rotation speeds is shown in Fig. 12. It can be seen that although the sound level of the 4-pole concentrated winding motor with the cylindrical core is higher than the others, the noise level of the 6-pole

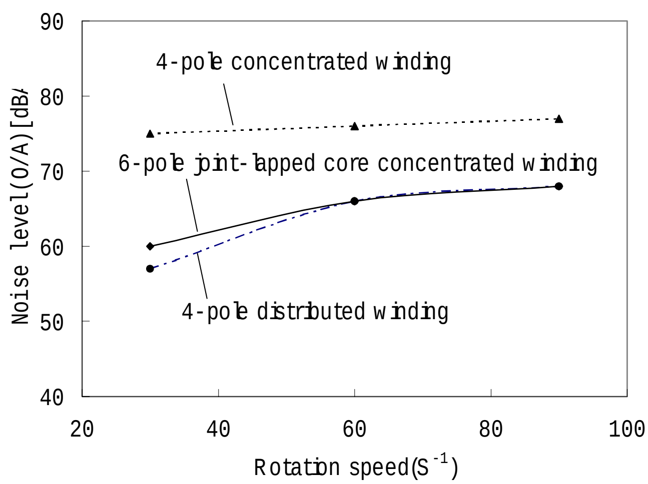


Fig. 12 Comparison of noise

concentrated winding motor with the joint-lapped core is equal to the noise level of the 4-pole distributed winding motor.

CONCLUSION

In this paper, we presented a study of a high efficiency brushless DC motor for compressors. We developed the new 6-pole concentrated winding motor, which is called “a joint-lapped core motor” and is produced by new manufacturing, and it brought the following result when compared to the conventional 4-pole distributed winding motor.

(1) Copper loss was reduced by 50%, iron loss was reduced by 20% under rated conditions and motor efficiency was improved by 3%.

(2) Noise, which was a problem in a conventional concentrated winding motor, was improved to equal the level of a distributed winding motor.

We achieved both high efficiency and low noise.

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